Large (non-small) x at the EIC
Jefferson Lab, October 4, 2016

Pion structure from leading nucleon production

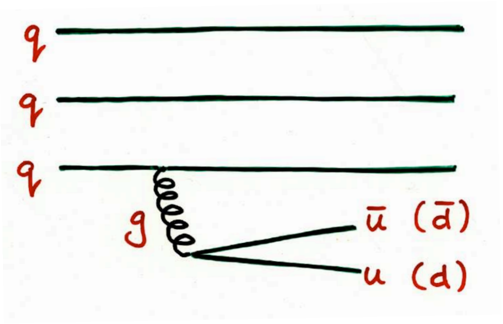
Wally Melnitchouk

Jefferson Lab

with Chueng Ji (NCSU), *Josh McKinney* (UNC),
Nobuo Sato (JLab), *Tony Thomas* (Adelaide)

Light quark sea

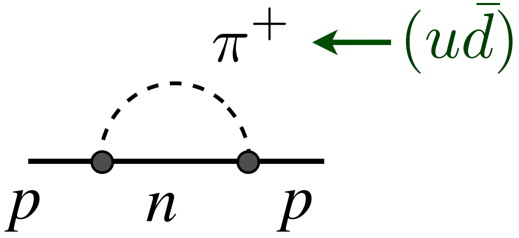
- From perturbative QCD expect symmetric $q\bar{q}$ sea generated by gluon radiation into $q\bar{q}$ pairs (if quark masses are the same)



$\longrightarrow$ since u and d quarks nearly degenerate, expect flavor-symmetric light-quark sea

$$\bar{d} \approx \bar{u}$$

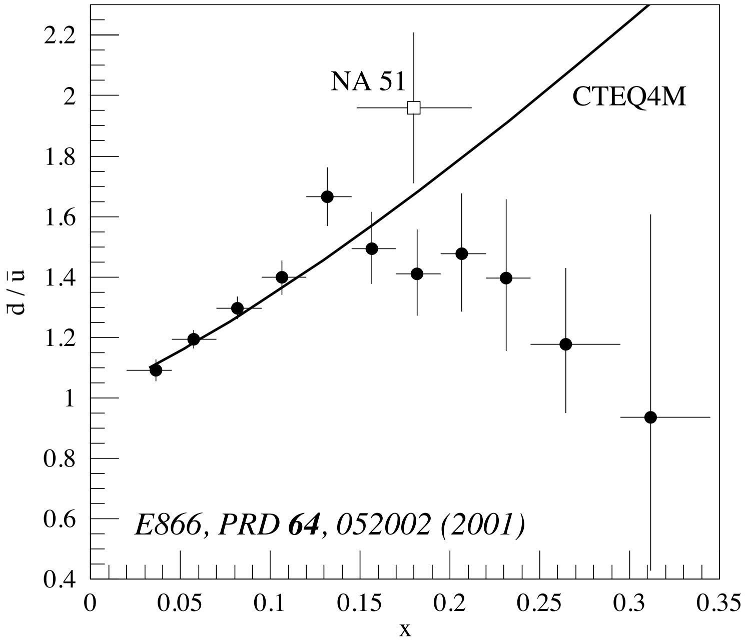
- In 1980s Thomas argued that chiral symmetry of QCD (important at low energies) should have consequences for antiquark PDFs in the nucleon (at high energies)

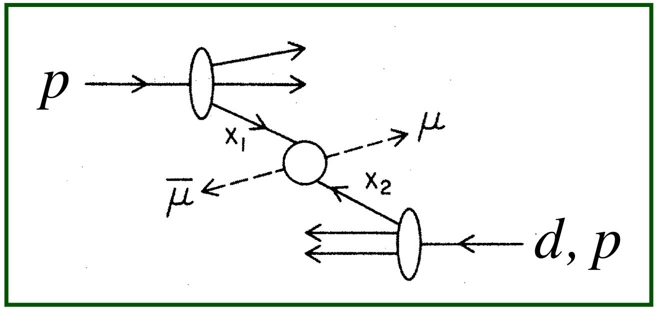


$$\longrightarrow \quad \boxed{\bar{d} > \bar{u}}$$

Light quark sea

- Asymmetry spectacularly confirmed in high-precision DIS and Drell-Yan experiments





$$\frac{d\sigma}{dx_1 dx_2} \sim \sum_q e_q^2\, q(x_1)\,\bar{q}(x_2) \;+\; (x_1 \leftrightarrow x_2)$$

$$\frac{\sigma^{pd}}{\sigma^{pp}} \approx 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \quad \text{for } x_1 \gg x_2$$

→ strongly suggested role of chiral symmetry and pion cloud as central to understanding of nucleon’s quark structure

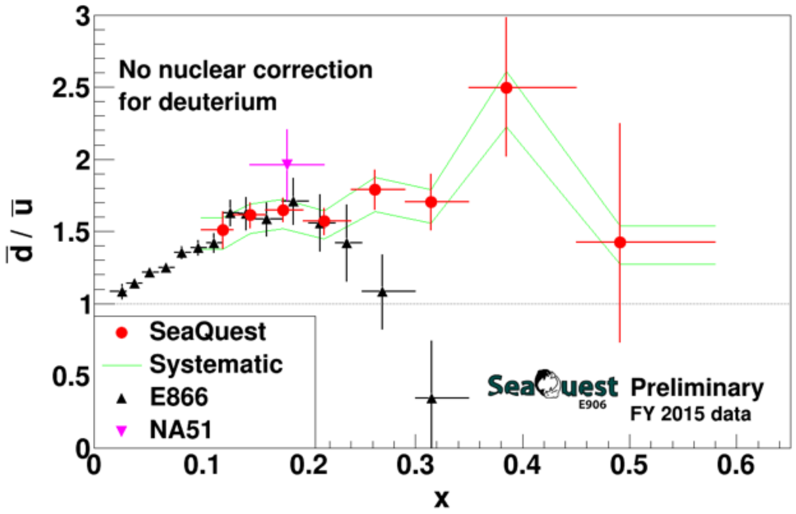
$$(\bar{d} - \bar{u})(x) = (f_\pi \otimes \bar{q}_\pi)\,(x)$$

pion distribution
in nucleon

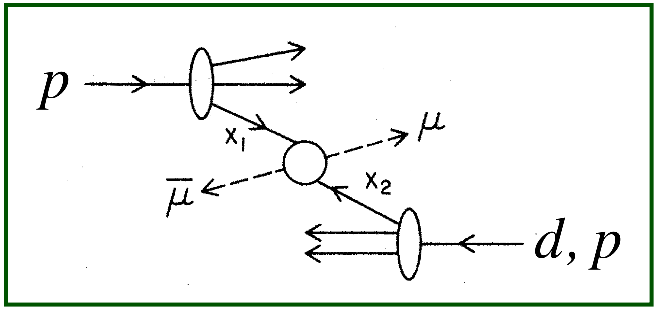
pion PDF

Light quark sea

- Asymmetry spectacularly confirmed in high-precision DIS and Drell-Yan experiments



P. Reimer (2016)



$$\frac{d\sigma}{dx_1 dx_2} \sim \sum_q e_q^2\, q(x_1)\, \bar{q}(x_2) \; + \; (x_1 \leftrightarrow x_2)$$

$$\frac{\sigma^{pd}}{\sigma^{pp}} \approx 1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)} \quad \text{for } x_1 \gg x_2$$

→ strongly suggested role of chiral symmetry and pion cloud as central to understanding of nucleon's quark structure

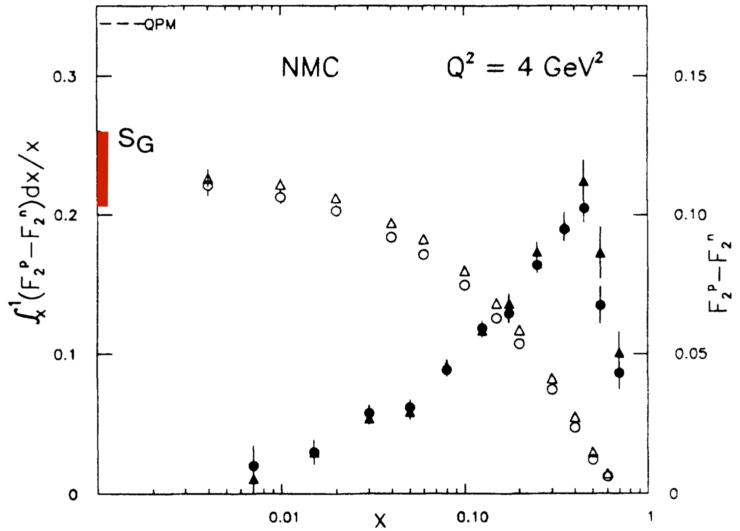
$$(\bar{d} - \bar{u})(x) = (f_\pi \otimes \bar{q}_\pi)\,(x)$$

pion distribution
in nucleon

pion PDF

Light quark sea

- Asymmetry spectacularly confirmed in high-precision DIS and Drell-Yan experiments



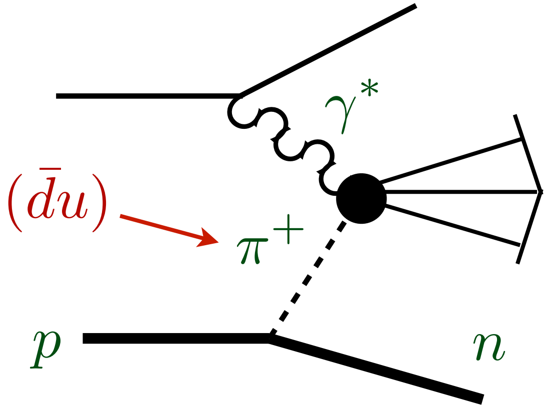
NMC (1994)

$$\int_0^1 \frac{dx}{x}(F_2^p - F_2^n) = \frac{1}{3} - \frac{2}{3}\int_0^1 dx\,(\bar{d} - \bar{u})$$

$$= 0.235(26)$$

violation of Gottfried sum rule!

→ Sullivan process — DIS from pion cloud of the nucleon



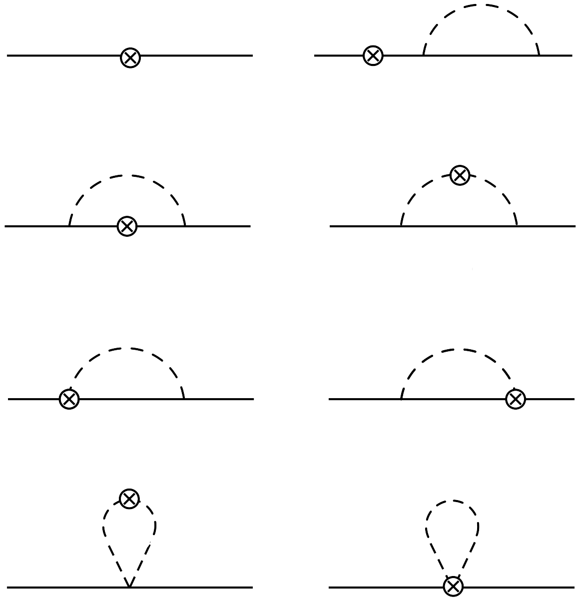
Sullivan (1972)

Chiral effective theory

- Early calculations used phenomenological models — more recently rigorous connection with QCD established via effective chiral field theory

$$\mathcal{L}_{\rm eff} = \frac{g_A}{2f_\pi}\,\bar{\psi}_N\gamma^\mu\gamma_5\,\vec{\tau}\cdot\partial_\mu\vec{\pi}\,\psi_N - \frac{1}{(2f_\pi)^2}\,\bar{\psi}_N\gamma^\mu\,\vec{\tau}\cdot(\vec{\pi}\times\partial_\mu\vec{\pi})\,\psi_N$$

Weinberg (1967)



→ lowest order πN interaction includes pion rainbow and tadpole contributions

→ matching quark- and hadron-level operators

$$\mathcal{O}_q^{\mu_1\cdots\mu_n} = \sum_h c_{q/h}^{(n)}\;\mathcal{O}_h^{\mu_1\cdots\mu_n}$$

yields convolution representation

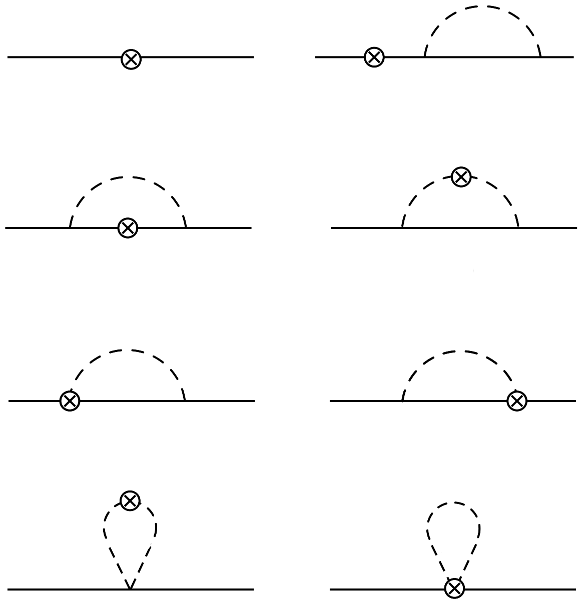
$$q(x) = \sum_h \int_x^1 \frac{dy}{y}\,f_h(y)\,q_v^h(x/y)$$

Chiral effective theory

- Early calculations used phenomenological models — more recently rigorous connection with QCD established via effective chiral field theory

$$\mathcal{L}_{\rm eff} \;=\; \frac{g_A}{2f_\pi}\,\bar\psi_N\gamma^\mu\gamma_5\,\vec\tau\cdot\partial_\mu\vec\pi\,\psi_N \;-\; \frac{1}{(2f_\pi)^2}\,\bar\psi_N\gamma^\mu\,\vec\tau\cdot(\vec\pi\times\partial_\mu\vec\pi)\,\psi_N$$

Weinberg (1967)



→ expanding PDF moments in powers of m_π, coefficients of leading nonanalytic (LNA) terms are model-independent!

Thomas, WM, Steffens (2000)
Chueng Ji, WM, Thomas (2012)

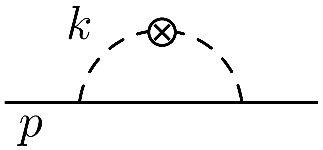
→ nonanalytic behavior vital for chiral extrapolation of lattice data on PDF moments

$$\langle x\rangle_{u-d}^{\rm LNA} \;\sim\; m_\pi^2\,\log m_\pi^2$$

Detmold et al. (2001)

Pion splitting functions

- Spitting functions for various diagrams computed in chiral theory *e.g.* pion rainbow diagram



$$f_\pi(y) = f^{(\text{on})}(y) + f^{(\delta)}(y)$$

has on-shell $(y = k^+/p^+ > 0)$ and $\delta(y)$ contributions!

$$f^{(\text{on})}(y) = \frac{g_A^2 M^2}{(4\pi f_\pi)^2} \int dk_\perp^2 \, \frac{y(k_\perp^2 + y^2 M^2)}{[k_\perp^2 + y^2 M^2 + (1-y)m_\pi^2]^2}$$

$$f^{(\delta)}(y) = \frac{g_A^2}{4(4\pi f_\pi)^2} \int dk_\perp^2 \, \log\left(\frac{k_\perp^2 + m_\pi^2}{\mu^2}\right) \delta(y)$$

- For point-like nucleons and pions, integrals divergent

$\longrightarrow$ finite size of nucleon provides natural regularization scale (but does not prescribe form of regularization)

$\mathcal{F} = \Theta(\Lambda^2 - k_\perp^2)$ $k_\perp$ cutoff

$\mathcal{F} = \left(\frac{\Lambda^2 - m_\pi^2}{\Lambda^2 - t}\right)$ t monopole

$\mathcal{F} = \exp\left[(t - m_\pi^2)/\Lambda^2\right]$ t exponential

$\mathcal{F} = \exp\left[(M^2 - s)/\Lambda^2\right]$ s-dep. exponential

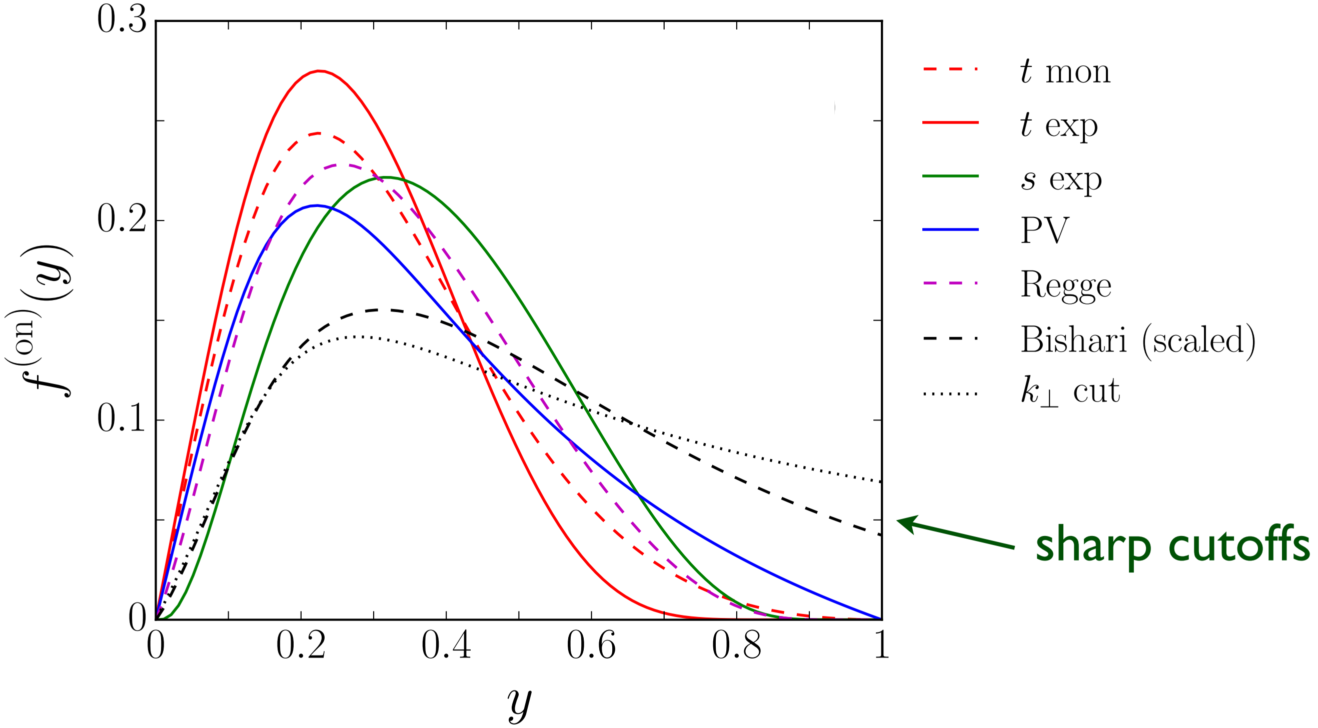
$\mathcal{F} = \left[1 - \frac{(t - m_\pi^2)^2}{(t - \Lambda^2)^2}\right]^{1/2}$ Pauli-Villars

$\mathcal{F} = y^{-\alpha_\pi(t)} \exp\left[(t - m_\pi^2)/\Lambda^2\right]$ Regge

Pion splitting functions

- Detailed shape of splitting function depends on regularization, but common general features

e.g. on-shell function



$\mathcal{F} = \Theta(\Lambda^2 - k_\perp^2)$ $k_\perp$ cutoff

$\mathcal{F} = \left(\frac{\Lambda^2 - m_\pi^2}{\Lambda^2 - t}\right)$ t monopole

$\mathcal{F} = \exp\left[(t - m_\pi^2)/\Lambda^2\right]$ t exponential

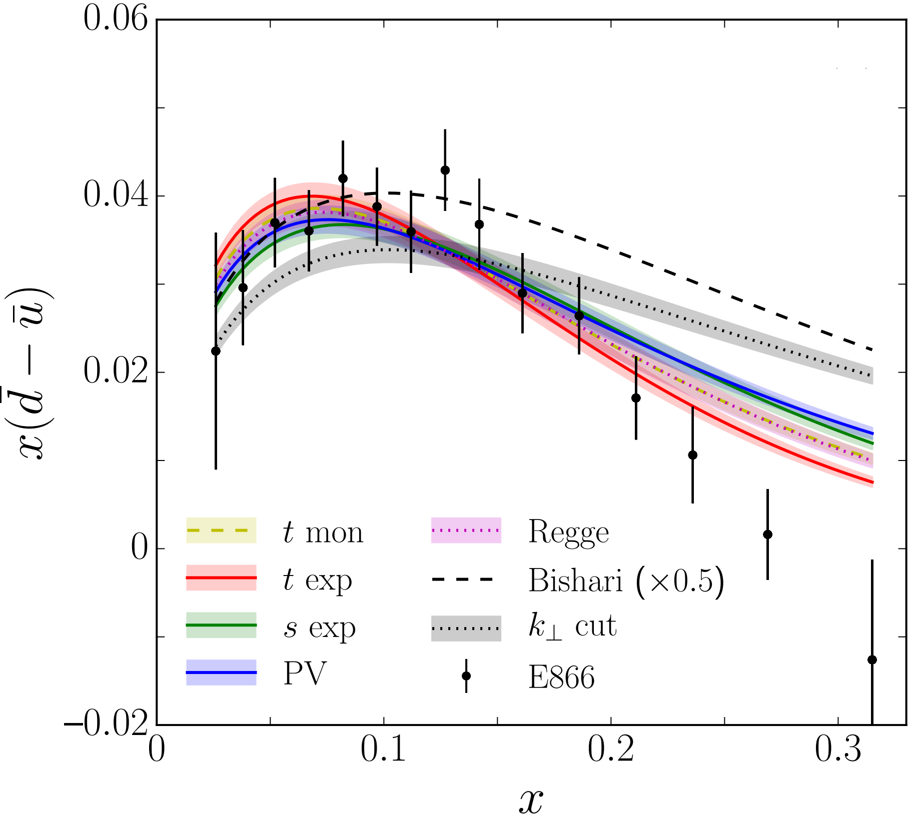
$\mathcal{F} = \exp\left[(M^2 - s)/\Lambda^2\right]$ s-dep. exponential

$\mathcal{F} = \left[1 - \frac{(t - m_\pi^2)^2}{(t - \Lambda^2)^2}\right]^{1/2}$ Pauli-Villars

$\mathcal{F} = y^{-\alpha_\pi(t)} \exp\left[(t - m_\pi^2)/\Lambda^2\right]$ Regge

Pion splitting functions

- E866 $\bar{d} - \bar{u}$ data can be fitted with range of regulators



average pion "multiplicity"

$$\langle n \rangle_{\pi N} = 3 \int_0^1 dy\, f_N^{(\mathrm{on})}(y)$$

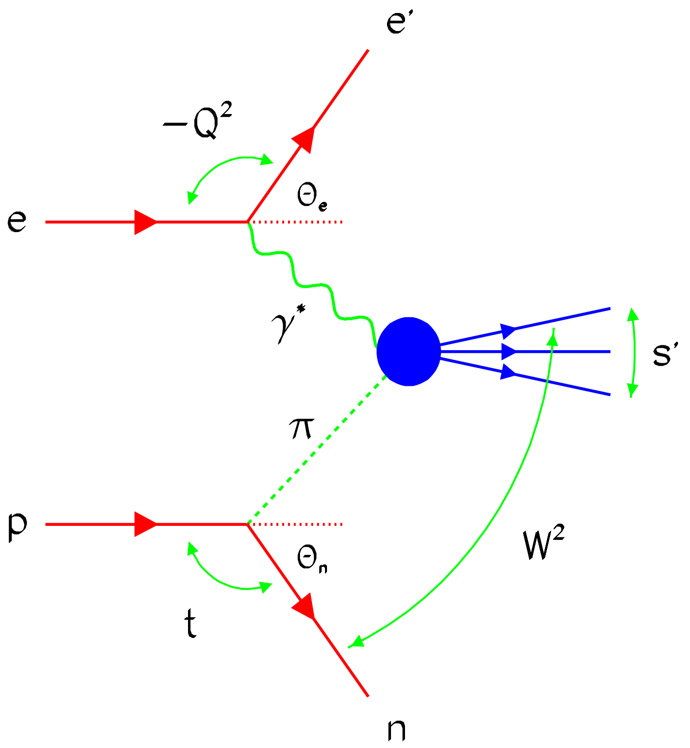
$$\sim \ 0.25 - 0.3$$

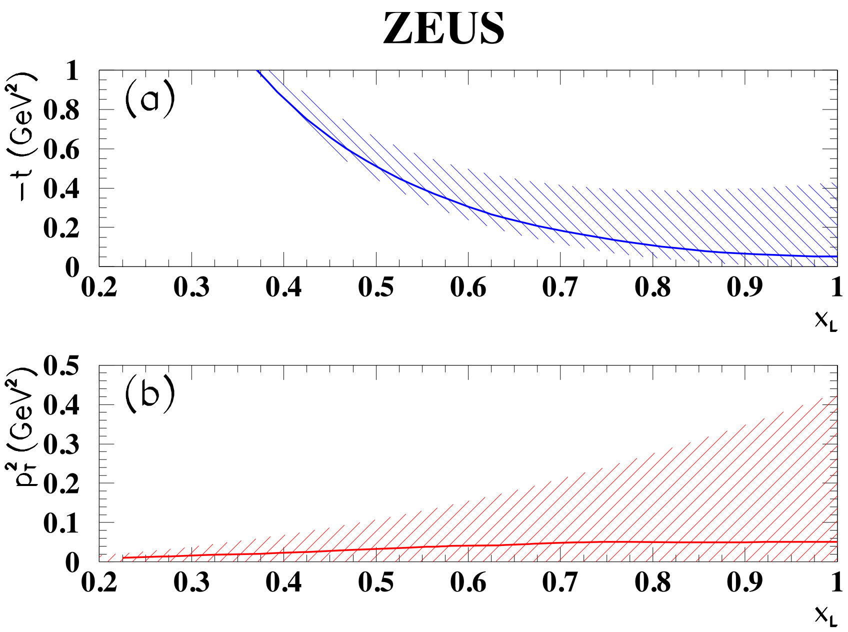
→ with exception of $k_\perp$ cutoff and Bishari models,
all others give reasonable fits, $\chi^2 \lesssim 1.5$

→ are there other data that can be more discriminating?

Leading neutron production at HERA

- ZEUS & H1 collaborations measured spectra of neutrons produced at very forward angles, $\theta_n < 0.8\ \mathrm{mrad}$





$$x_L \approx 1 - y$$

→ can data be described within same framework as E866 asymmetry?

→ simultaneous fit never previously been performed!

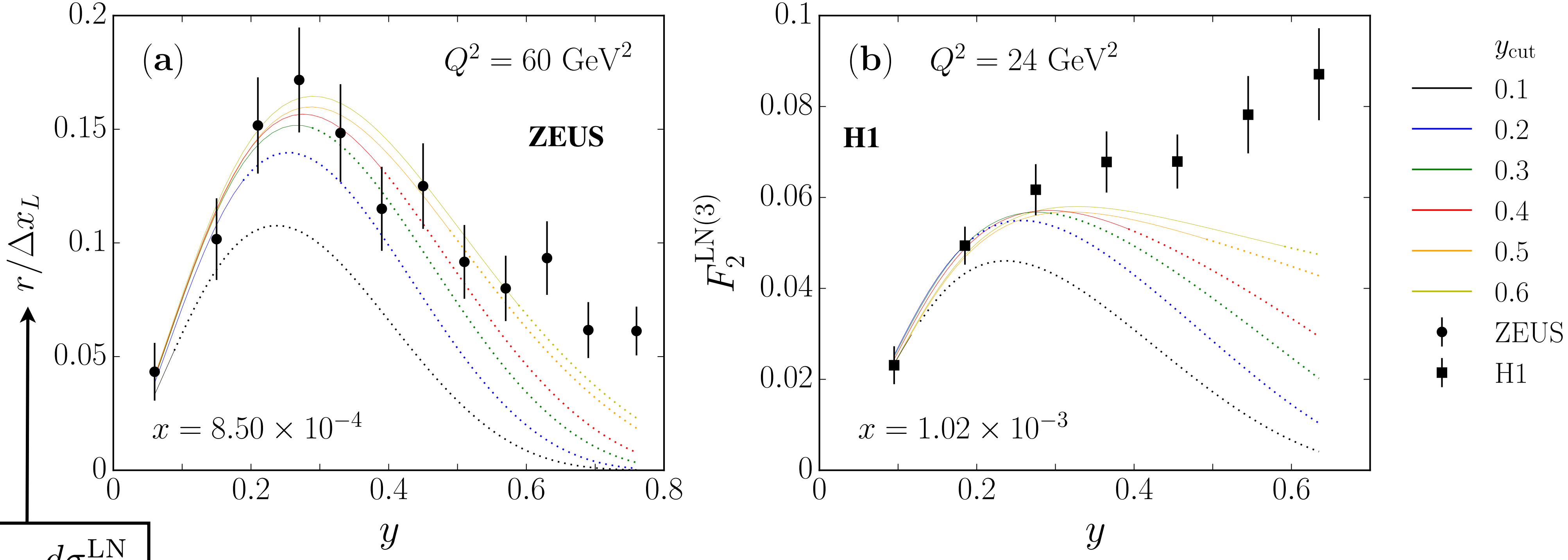
Leading neutron production at HERA

- Measured LN differential cross section (integrated over $p_\perp$)

$$\frac{d^3\sigma^{\rm LN}}{dx\,dQ^2\,dy} \;\sim\; F_2^{\rm LN(3)}(x,Q^2,y)$$

$$\boxed{2 f_N^{\rm (on)}(y)\, F_2^\pi(x/y,Q^2)}$$ for π exchange

e.g.

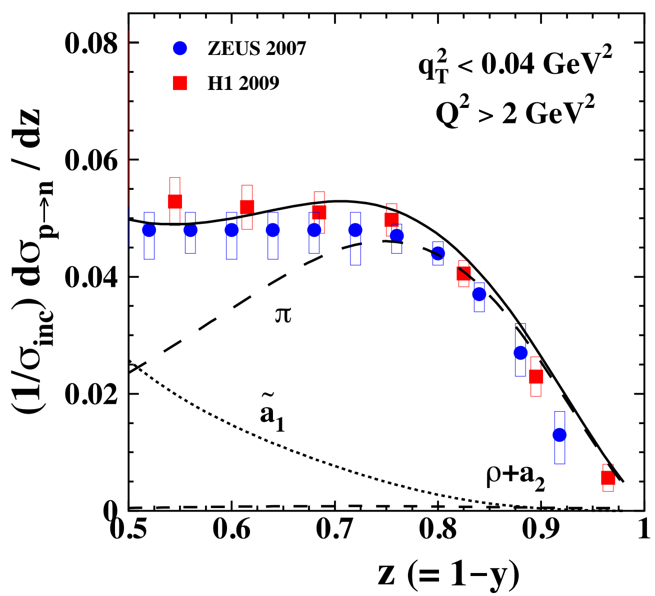


$$\boxed{r = \frac{d\sigma^{\rm LN}}{d\sigma^{\rm inc}}}$$

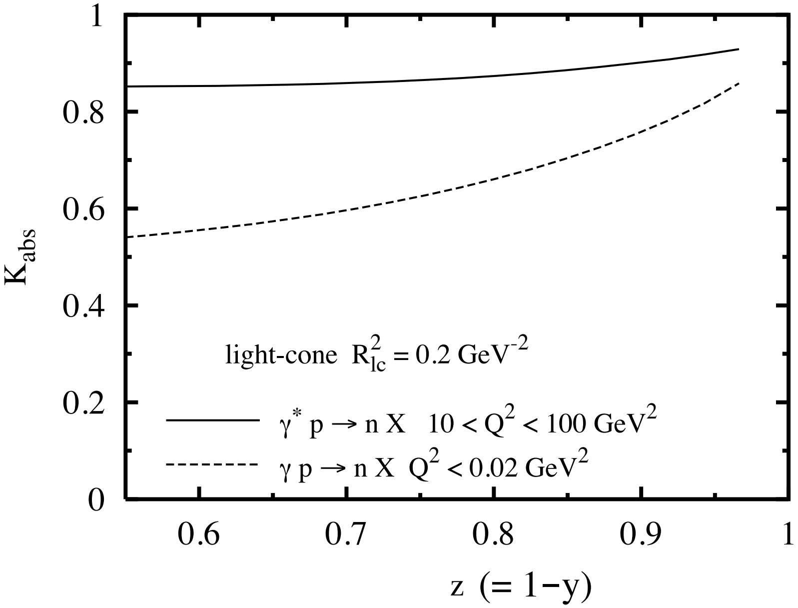
$\longrightarrow$ quality of fit depends on range of y fitted

Leading neutron production at HERA

- At large y non-pionic mechanisms contribute
  ($e.g.$ heavier mesons, absorption)



Kopeliovich et al. (2012)

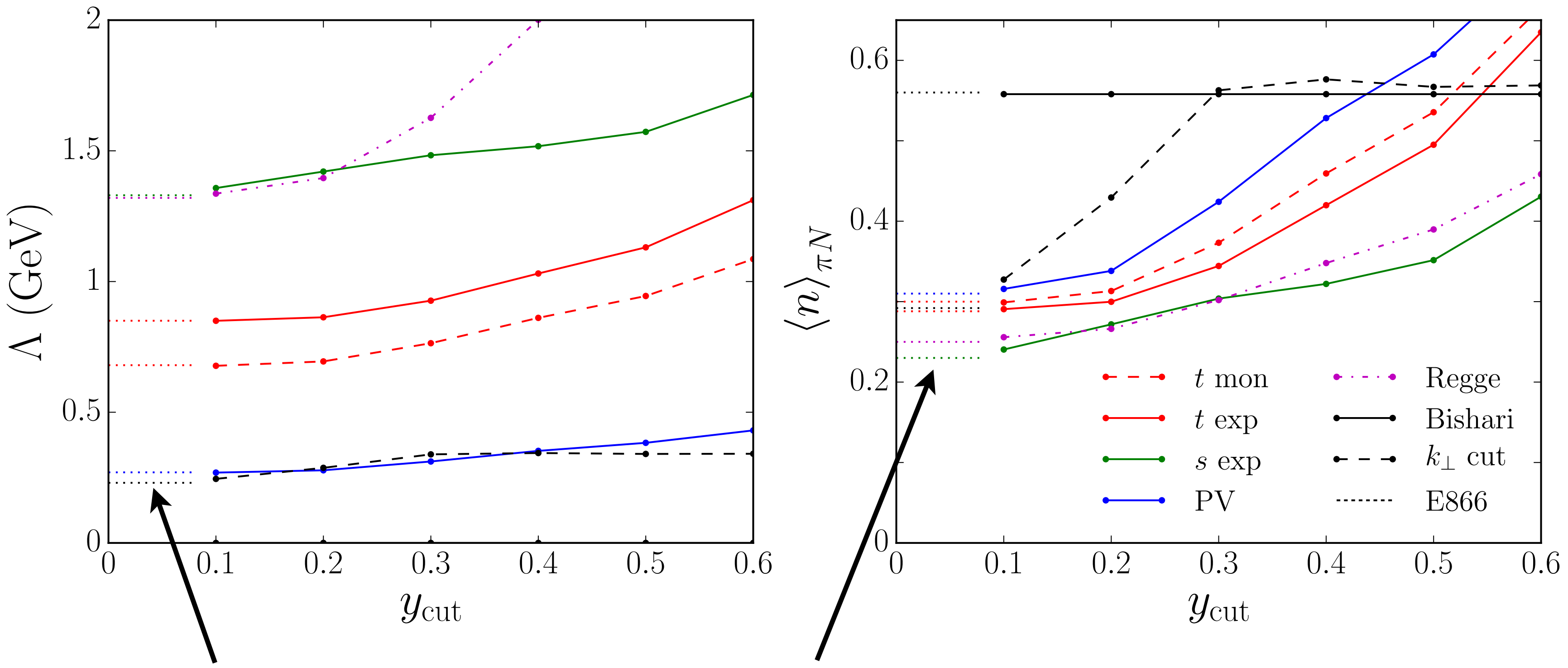


D'Alesio, Pirner (2000)

- To reduce model dependence, fit the value of $y_{\rm cut}$
  up to which data can be described in terms of π exchange

Leading neutron production at HERA

- Fit requires higher momentum pions with increasing $y_{\rm cut}$

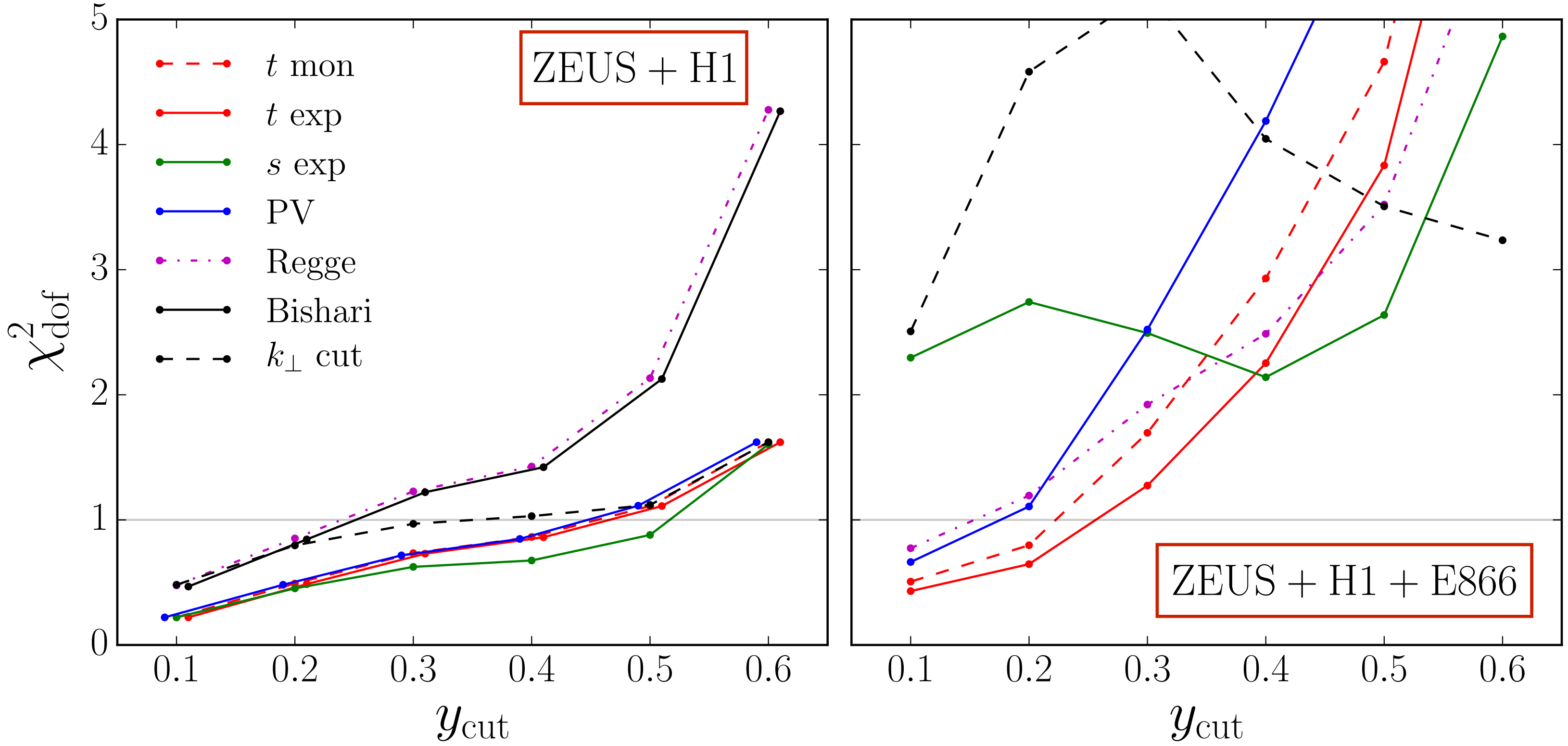


values from fit to E866 data only

→ larger values of $y_{\rm cut}$ more in conflict with E866 data

Leading neutron production at HERA

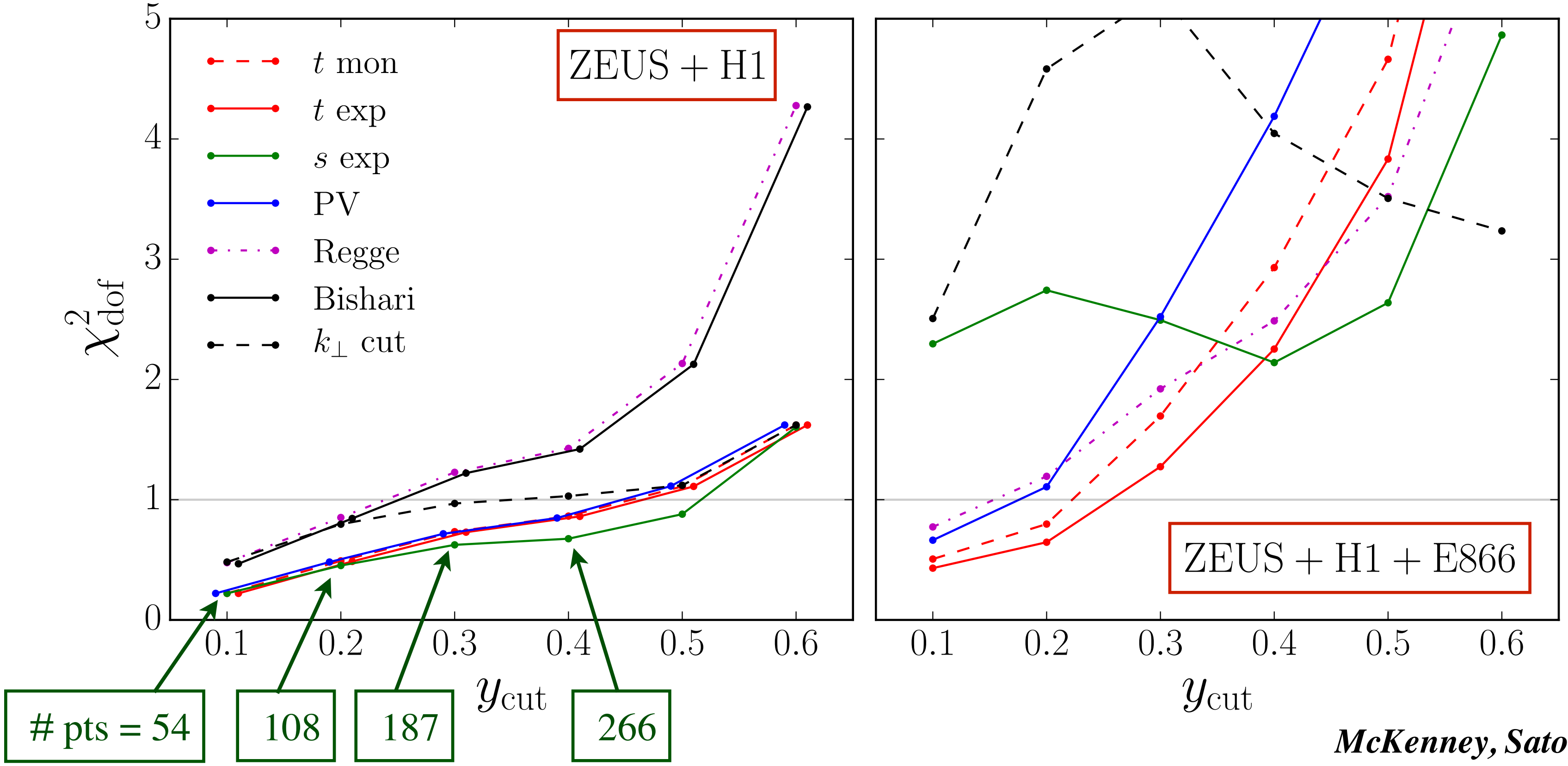
- Combined fit to HERA LN and E866 Drell-Yan data



McKenney, Sato, WM, Ji (2016)

Leading neutron production at HERA

- Combined fit to HERA LN and E866 Drell-Yan data

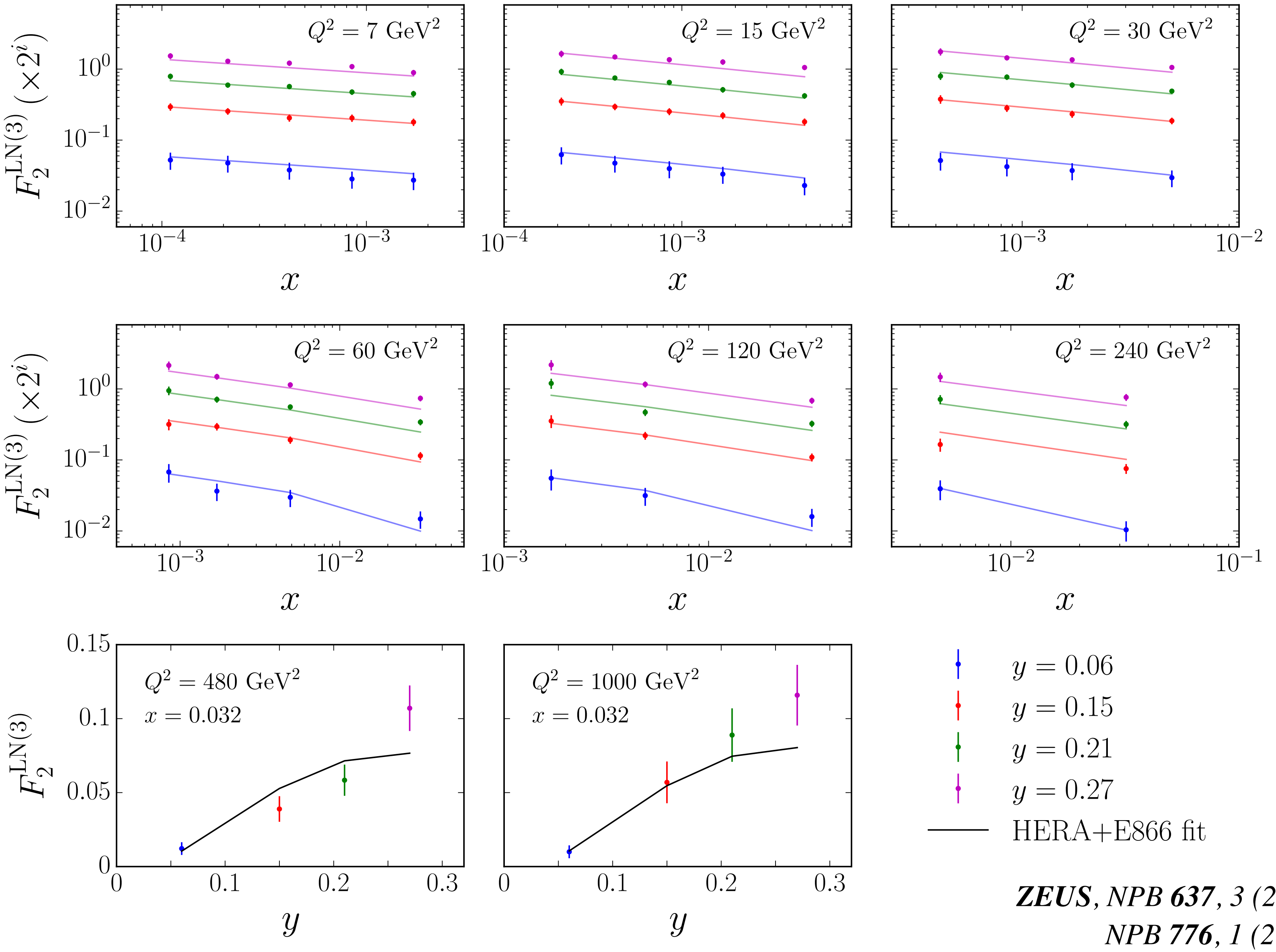


McKenney, Sato, WM, Ji (2016)

→ best fits for largest number of points afforded by t-dependent exponential (and t monopole) regulators

Leading neutron production at HERA

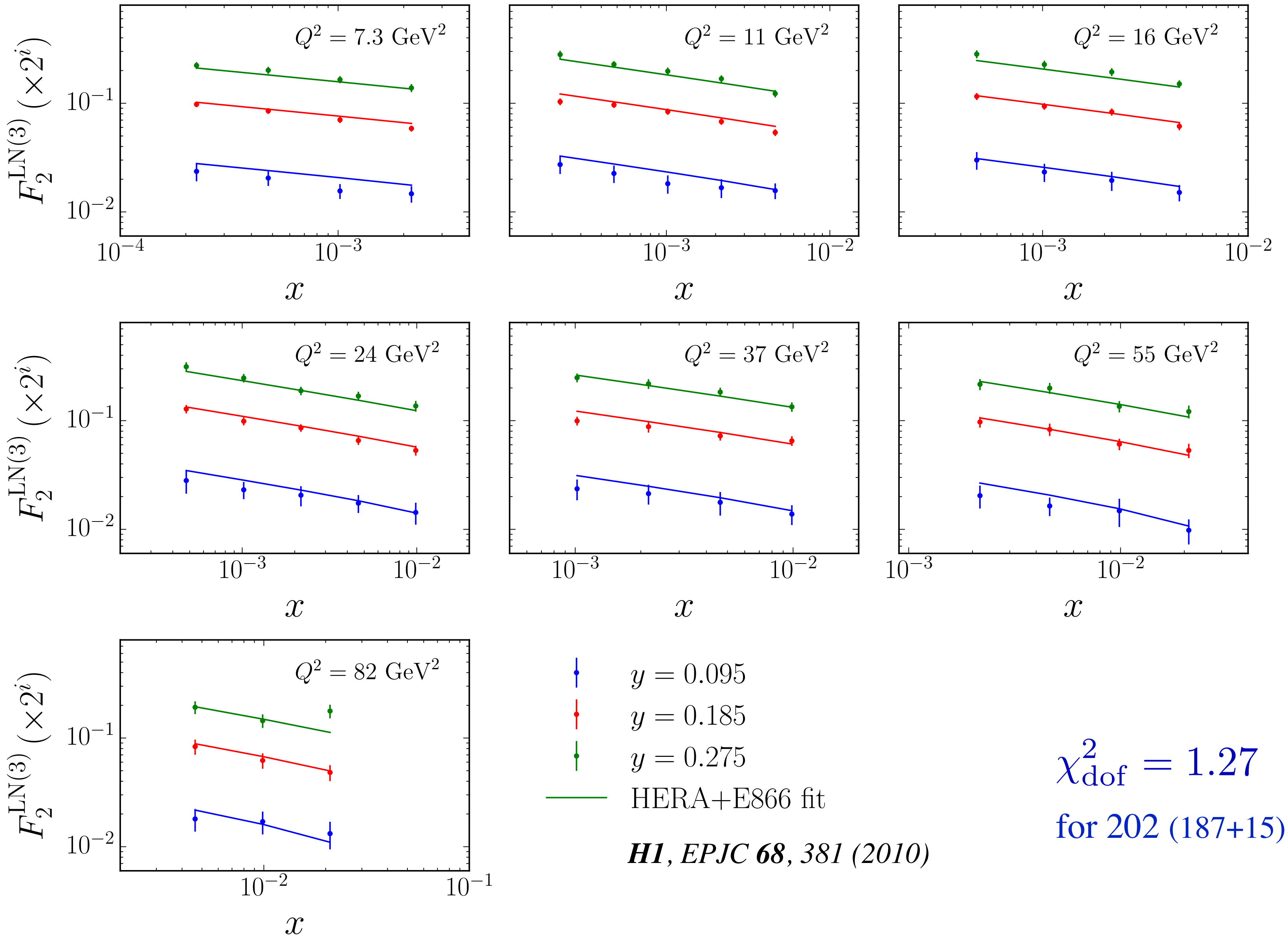
- Fit to ZEUS LN spectra for $y_{\rm cut} = 0.3$ (t-dependent exponential)



***ZEUS**, NPB **637**, 3 (2002)*
*NPB **776**, 1 (2007)*

Leading neutron production at HERA

- Fit to H1 LN spectra for $y_{\text{cut}} = 0.3$ (t-dependent exponential)

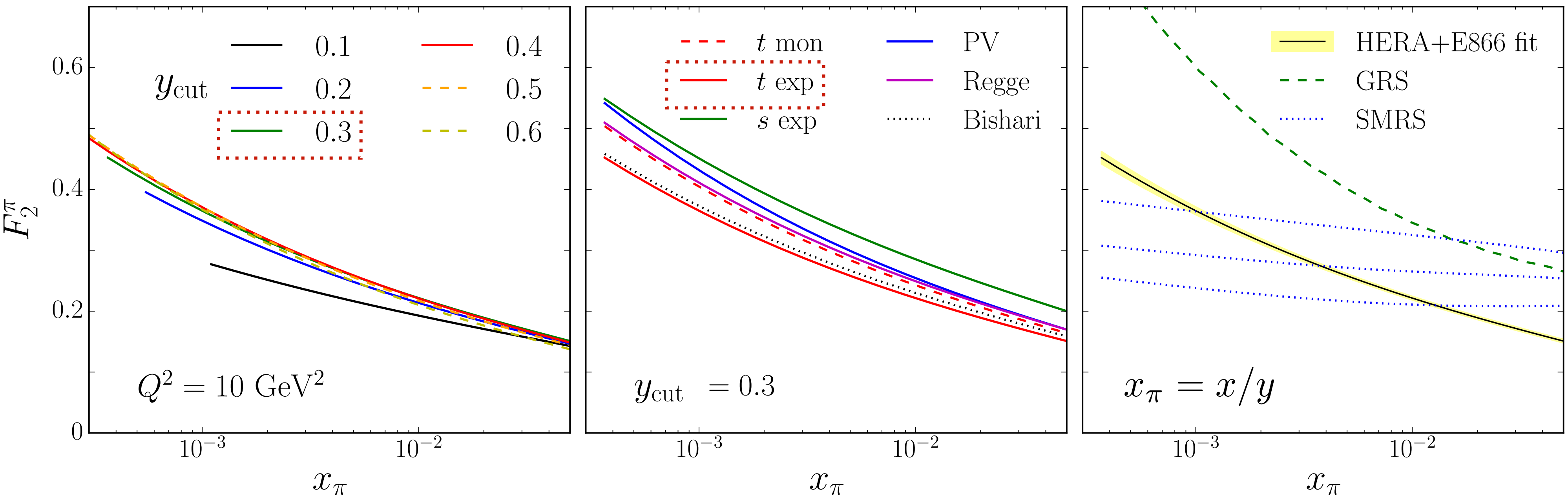


***H1**, EPJC **68**, 381 (2010)*

$\chi^2_{\text{dof}} = 1.27$

for 202 (187+15) points

Extracted pion structure function



$$F_2^\pi = N\, x_\pi^a\, (1 - x_\pi)^b, \quad a = a_0 + a_1 \eta$$

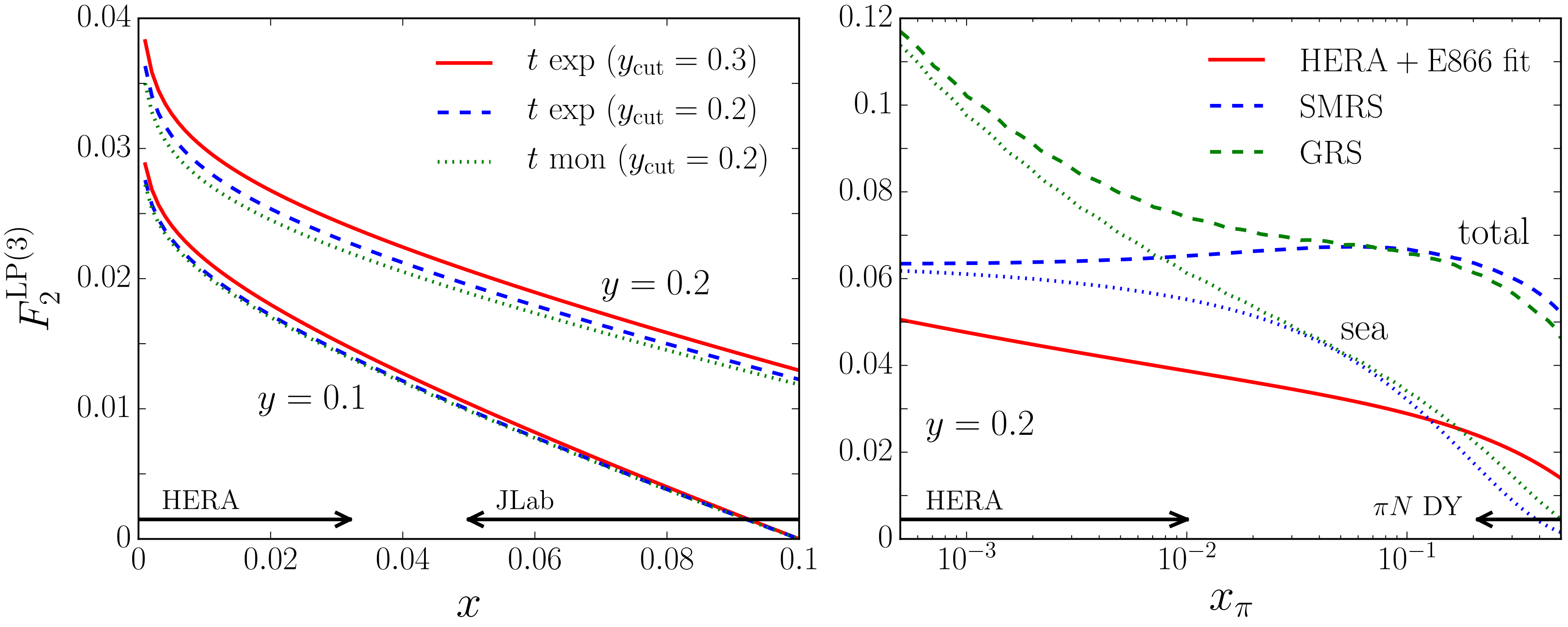
$$\eta \sim \log(\log Q^2)$$

McKenney, Sato, WM, Ji (2016)

→ stable values of F_2^π at $4 \times 10^{-4} \lesssim x_\pi \lesssim 0.03$ from combined fit

→ shape similar to GRS fit to πN Drell-Yan data (for $x_\pi \gtrsim 0.2$), but smaller magnitude

Predictions at TDIS kinematics



McKenney, Sato, WM, Ji (2016)

→ JLab TDIS experiment can fill gap in x_π coverage between HERA and πN Drell-Yan kinematics

Outlook

- Combined analysis can be extended by including πN DY data

  ⟶ constrain large-x_π region $(x_\pi \gtrsim 0.2)$

- Generalize parametrization by fitting individual pion valence and sea quark PDFs, rather than F_2^π

- Longer-term goal is to use all data sensitive to pion structure (including TDIS, EIC) to constrain pion PDFs over full range $10^{-4} \lesssim x_\pi \lesssim 1$

  ⟶ global analysis under way of HERA LN, Drell-Yan $\pi N + pd/pp$ (+ future JLab TDIS data) to determine pion PDFs at all x

  Patrick Barry, Chueng Ji (NCSU), Nobuo Sato, WM (2016)